A Heterogeneous Multiscale Method for Efficient Simulation of Power Systems with Inverter-Based Resources

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Project Duration: 03/2024 – 02/2027
Funding Source: National Science Foundation (NSF)

Summary

This project presents a novel simulation framework for power systems with high penetration of inverter-based resources (IBRs), where system dynamics span multiple timescales ranging from microsecond-level electromagnetic transients (EMT) to slower electromechanical responses. Such multi-timescale behavior leads to highly stiff nonlinear models, making conventional time-domain simulations computationally expensive due to the requirement of extremely small-time steps for numerical stability. Existing approaches, including co-simulation and offline model reduction, often suffer from interface inconsistencies, reduced accuracy, and difficulty in defining appropriate system partitions. To address these challenges, this work proposes a Heterogeneous Multiscale Method (HMM)–based framework that enables efficient and accurate simulation directly on full EMT models without requiring explicit model reduction.

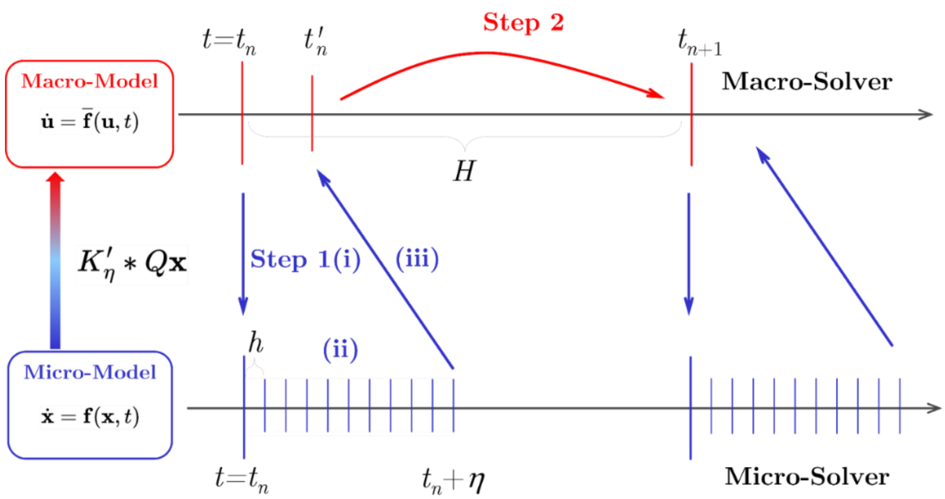

Figure 1: A two-timescale HMM scheme.

The core idea of the proposed method is to alternate between two complementary processes: a micro-process that resolves detailed EMT dynamics and a macro-process that advances slower system dynamics using significantly larger time steps. As illustrated in Fig. 1, the framework repeatedly performs short bursts of detailed micro-simulations over a small time interval to extract essential system behavior, followed by long macro-steps that evolve the system efficiently. Instead of constructing an explicit reduced-order model, the method estimates macroscopic dynamics on the fly using a kernel-based averaging technique applied to the micro-state trajectories. This allows the framework to adapt to system conditions dynamically while preserving both fast and slow dynamics of interest.

A key contribution of this work is the introduction of transformation operators that link micro-state variables to macro-state representations. These operators enable seamless transitions between the two processes without loss of accuracy. In addition, the framework incorporates a semi-analytical Differential Transformation (DT) method as the micro-solver, allowing variable-step simulation with explicit error control. The macro-process further employs adaptive step-size control to balance computational efficiency and numerical accuracy. Theoretical analysis establishes bounds on the estimation error and provides insights into the relationship between step sizes, kernel parameters, and achievable speedup, demonstrating that significant acceleration can be achieved while maintaining controlled accuracy.

The overall workflow of the proposed approach is summarized in Fig. 2, where the simulation dynamically switches between micro- and macro-processes depending on system conditions. During fast transients such as faults, the method relies on detailed EMT simulation to accurately capture high-frequency dynamics. Once these fast dynamics decay, the algorithm transitions to macro-processes with enlarged time steps, significantly reducing computational cost while maintaining accuracy for slower dynamics.

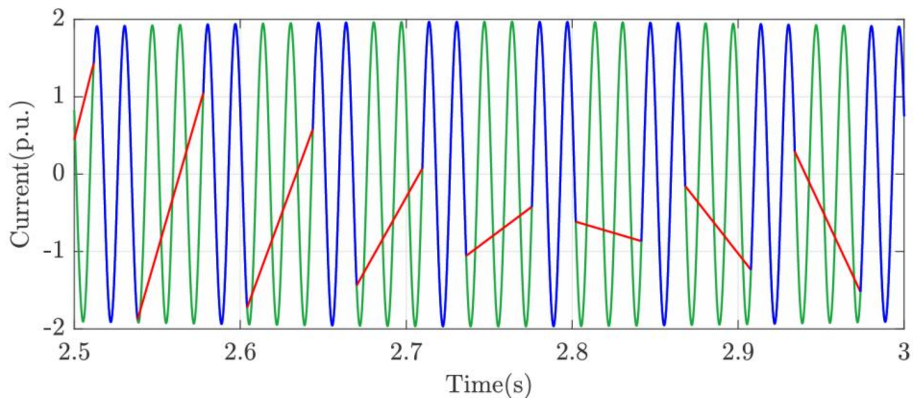

Figure 2: Simulation results for 390 bus system: Phase A current of the branch line 1-2.

The effectiveness and scalability of the proposed method are validated through case studies on a two-area system, the IEEE 39-bus system, and a large-scale 390-bus system. Simulation results show that the method accurately reproduces both fast transient responses and long-term dynamics, with substantial reductions in computational time compared to traditional EMT solvers. In particular, the method achieves several-fold speedup in medium-scale systems and up to tens-of-times acceleration in large-scale simulations, while maintaining comparable accuracy to benchmark solutions.

Overall, the proposed HMM-based framework provides a unified and adaptive approach for multi-timescale power system simulation. By eliminating the need for explicit model reduction and enabling dynamic switching between timescales, it offers a scalable and robust solution for analyzing modern power systems with high IBR penetration. The framework is general and can be extended to incorporate additional timescales and more detailed device-level dynamics in future work.

PowerCascade: Power Systems Cascading Failure Analysis Synthetic Dataset

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Project Duration: 06/2025 – 08/2025
Funding Source: National Science Foundation (NSF)

Summary

The stability and reliability of power systems are critical concerns in modern energy infrastructure. As the power grid becomes increasingly complex due to the integration of renewables and distributed energy resources, the risk of cascading failures—sequential outages triggered by an initial fault—has grown substantially. Without timely intervention, these cascading events can escalate into widespread blackouts affecting millions of people, as evidenced by major incidents including the 2012 India blackout (affecting over 600 million), the 2019 Argentina–Uruguay–Paraguay blackout (48 million), and the 2011 Southwest U.S. event (2.7 million). Despite the severity of these events, the research community has lacked a standardized, high-quality dataset for developing and benchmarking AI-based methods for cascading failure analysis. This project introduces PowerCascade, a synthetic dataset specifically designed to support research on the application of artificial intelligence (AI) for learning and predicting the propagation of cascading failures in power systems.

The PowerCascade dataset is generated using an emulation framework inspired by the Oak Ridge–Pserc–Alaska (OPA) model and implemented in both MATLAB. The Northeast Power Coordinating Council (NPCC) 140-bus test system—comprising 140 buses and 233 transmission lines—serves as the testbed. Cascading failures are initiated by N-2 contingency events, i.e., the simultaneous outage of two transmission lines, representing the starting point of each simulation. The data generation workflow is illustrated in Fig. 1. For each simulation, the system is initialized with pre-fault conditions (bus voltage levels and active power injections) randomly sampled within a predefined range to ensure diversity across scenarios. The DC optimal power flow (OPF) model is then applied to re-dispatch generation following each fault, and overloaded lines are tripped to simulate system protection actions. This iterative process continues until no further failures occur, capturing the full cascade evolution. To comprehensively represent real-world operating conditions, emulation is conducted under three load scenarios: light load (0.8× base), normal load (1.0× base), and heavy load (1.2× base).

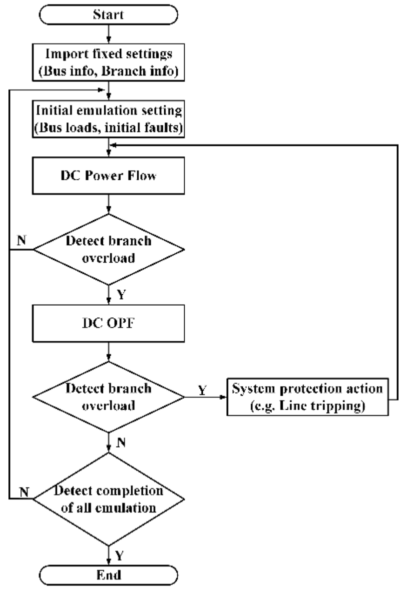

Figure 1: Data generation workflow of the PowerCascade dataset

The dataset is organized into two components: static parameters (Buses.csv and Branches.csv) capturing topology, impedances, and capacity limits; and dynamic failure records documenting branch outage sequences and bus load values across stages, in four CSV files by load condition plus a consolidated FailureData_All.csv. As shown in Fig. 2, the dataset contains 13,500 scenarios and 28,811 data entries in total.

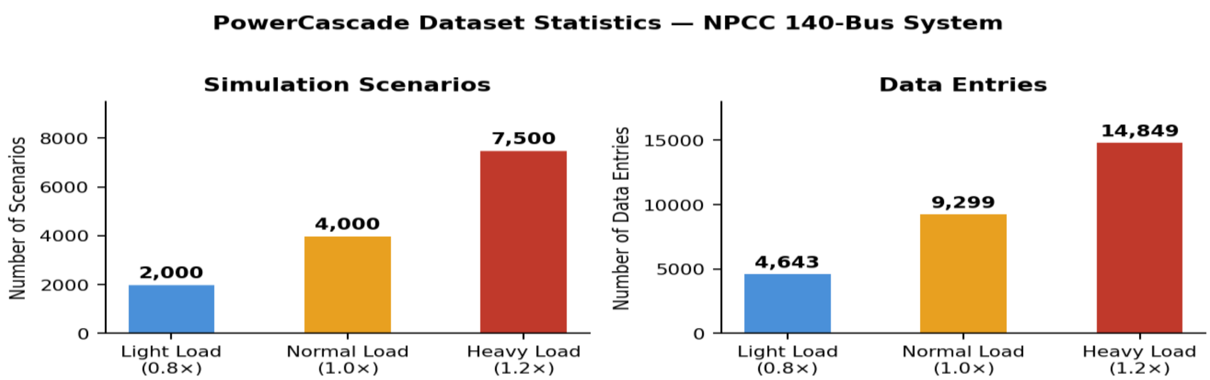

Figure 2: Dataset statistics across three load conditions: (a) simulation scenarios and (b) data entries

PowerCascade serves multiple research purposes. In power engineering, it enables AI-based failure prediction, mitigation, and grid resilience assessment. Its graph-structured nature makes it highly compatible with graph neural network (GNN) frameworks for node regression, edge classification, and graph classification. The naturally imbalanced failure distribution also makes it a benchmark for transfer learning and long-tail learning. The dataset is publicly available on IEEE DataPort (DOI: 10.21227/p3z3-f506), published in IEEE Data Descriptions (Volume 2, 2025).

Variable Time-Step Optimal Order Differential Transformation for Power System with IBR

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Project Duration: 12/2024 – 7/2025
Funding Source: National Science Foundation (NSF)

Summary

This project develops a dynamic simulation method for power systems with a high penetration of inverter-based resources (IBRs), aiming to improve the computational efficiency and numerical stability. Traditional numerical integration methods, such as Runge-Kutta methods, require very small time steps to guarantee the accuracy for stiff power system models, leading to significant computational burdens. Using the differential transformation (DT) method, the time step can be largely increased via high-order Taylor expansion, which greatly reduces the simulation time and improves the accuracy. Additionally, adaptive strategies are developed during the simulation to overcome the challenges of selecting the appropriate step size and order for the DT method.

Higher-order approximations significantly improve solution accuracy, enabling the use of larger time steps without sacrificing numerical stability. The DT method represents system trajectories using truncated power series, allowing efficient recursive computation of higher-order terms. A proportional-integral controller is introduced to regulate truncation error and dynamically adjust the time step size. In addition, an optimization-based order selection strategy is developed to determine the most efficient approximation order at each step.

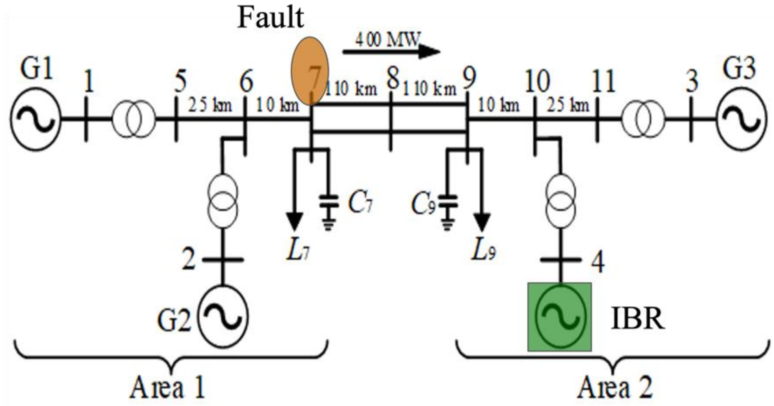
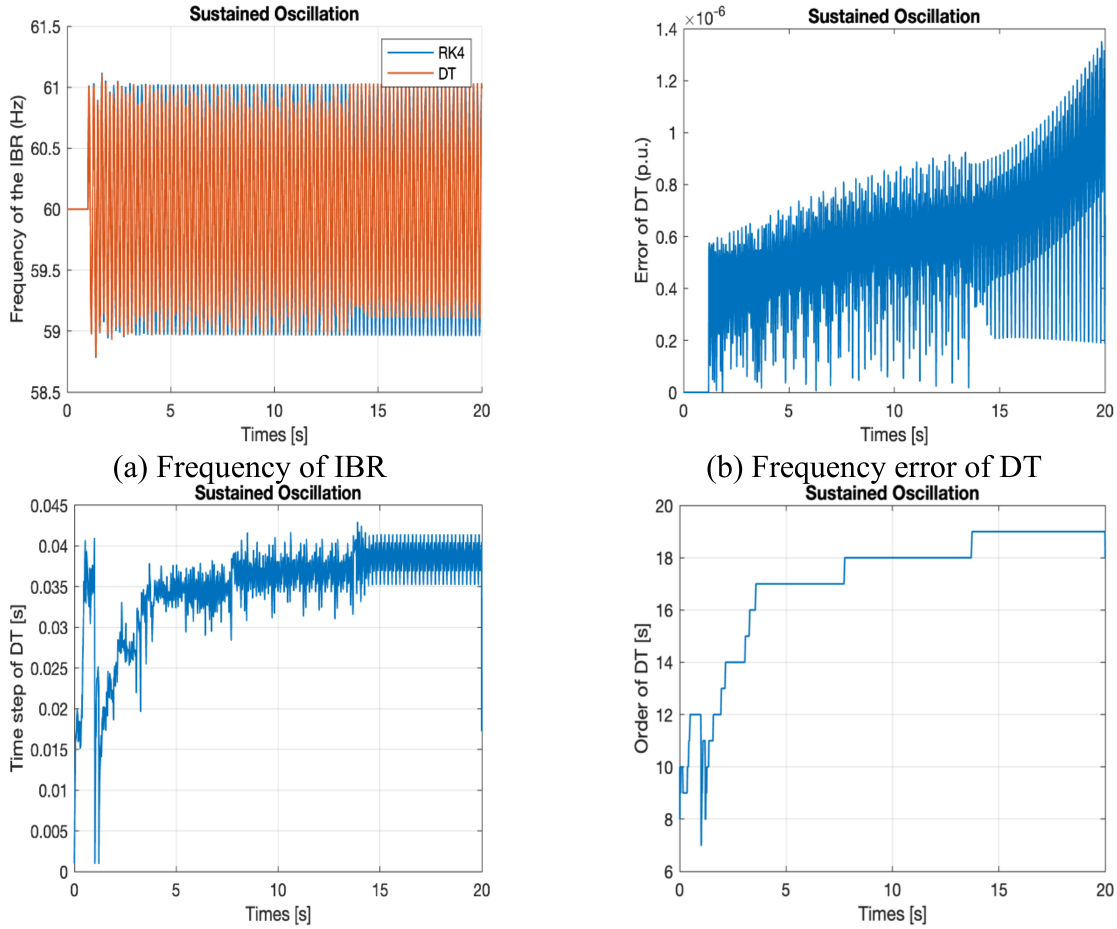


Figure 1: Kundur's two-area system

This study tests the DT method with variable time step and the approximation optimal order on Kundur's two-area system. As shown in Fig. 1, generator 4 is replaced by an IBR. A simplified IBR model with PLL and current PI-controlled regulation is used in the simulation. A 0.2 second three-phase grounding fault at bus 7 is considered. The simulation results are shown in Fig. 2. The frequency response in Fig. 2(a) demonstrates that the DT-based method accurately captures system dynamics and closely matches the benchmark RK4 solution. The error shown in Fig.2(b) remains on the order of 10^{-6} p.u., indicating high numerical accuracy.



(a) Frequency of IBR (b) Frequency error of DT

(c) Step-size of DT (d) Order of DT

Figure 2: Simulation results of Kundur's two-area system with IBR

This project provides an efficient and accurate simulation framework for power systems with high penetration of inverter-based resources. The proposed method improves computational efficiency while maintaining high accuracy. Compared with traditional numerical methods, it enables larger time steps and reduces simulation time, making it suitable for stiff power system models integrating IBR models.

A Voronoi Diagram-Based Approach for AC Optimal Power Flow

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Project Duration: 1/2025 – 9/2025	
Funding Source: National Science Foundation	

<u>Summary</u>

In this work, a new approach, shown in Fig. 1, is proposed to globally solve the AC OPF problem by exploiting the geometrical structure of the OPF search space through a computational geometry technique, the Voronoi diagram. Toward global optimization, the Voronoi diagram is applicable to characterize the search space of any dimension but requires sufficient sample points. In this paper, the sample points are efficiently added by using the continuous-projected gradient (CPG) method with enforced constraint restoration [18]. Specifically, the method constructs a fictitious nonlinear dynamical system that models the OPF solution process. The asymptotically stable equilibria of this system corresponds to local OPF solutions, whereas the other OPF critical stationary points, such as maxima and saddle points, with the OPF formulated as a minimization problem, cannot be asymptotically stable. To achieve global optimality, the Voronoi diagram provides a global, geometrical characterization of the search space by partitioning it into cells and refining it iteratively with new sampling points. These points are selected based on the geometry of the feasible set, as revealed by the diagram and heuristic insights derived from the nonlinear dynamical system.

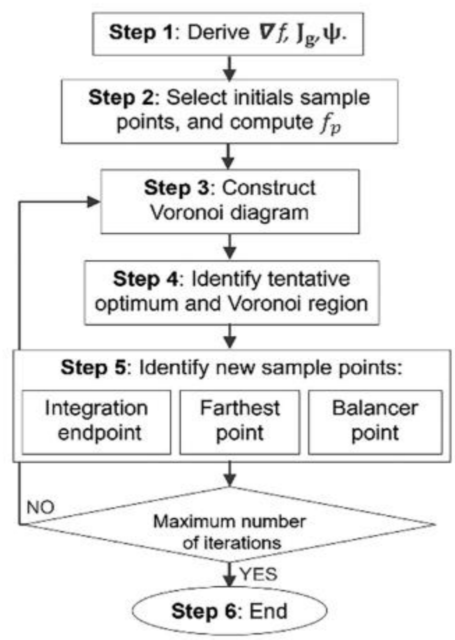

Figure 1: Flow chart

In Step 1, the proposed approach uses the CPG method with enforced constraint restoration to construct a nonlinear dynamical system described by an ordinary differential equation characterizing the flows leading to local optima. The penalized cost function constructed in Step 2 comprises the original cost function augmented by a penalty term proportional to the magnitude of constraint violations, which becomes zero when no violations are present. In Step 3 construct the Voronoi diagram is a computational geometry approach applicable to spaces of any dimension, an example is shown in Fig. 2. The candidate region, in Step 4, is defined as the Voronoi region containing the tentative optimal solution, identified as the sample point with the minimum cost function value. In the proposed approach, the CPG method with enforced constraint restoration is employed to upgrade the tentative optimum as illustrated in Fig. 3. In Step 5, enhancing the tentative optimum and improving the global approximation fidelity are two primary objectives that can be served by adding new sample points.

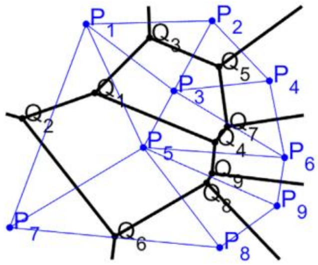

Figure 2: Voronoi Diagram

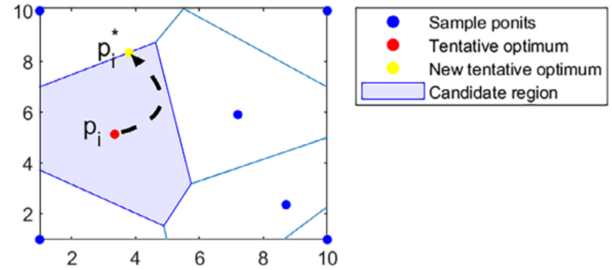

Figure 3: Candidate Region and Tentative Optimum

<u>Case Studies</u>

IEEE 9-Bus System: The feasible set is five dimensions: the real output power of two generators, denoted as $PG2$ and $PG3$, along with the voltage magnitudes $V1$, $V2$ and $V3$.

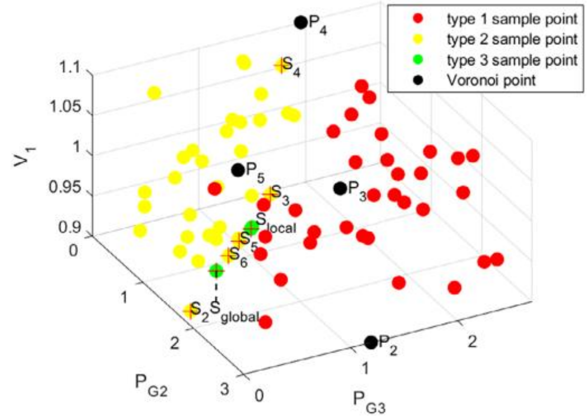

Figure 4: Case9mod: global OPF is achieved at Iteration 6

Table 1 provides a consolidated comparison of the objective value, computation time and optimality gap. As shown in the table, the proposed method achieves an optimality gap below 0.001% in all cases, whereas IPOPT failed to find the global optimum for the 'WB5mod' case starting from a flat initialization. In terms of runtime, the proposed method can be slower, especially for larger systems due to the time required to construct and compute Voronoi diagrams.

Table 1: Comparison between Voronoi-OPF and IPOPT

	Voronoi-OPF			IPOPT		
	Cost ($/hr)	Time (sec)	Optimality gap (%)	Cost ($/hr)	Time (sec)	Optimality gap (%)
WB5mod	139873	0.01125	< 0.001	161921	0.0209	15.76
Case9mod	3087.8	0.0919	< 0.001	3087.8	0.0780	< 0.001
Case39mod2	941.7	0.3325	< 0.001	941.7	0.1024	< 0.001
Case118mod	129625	10.9387	< 0.001	129625	0.1301	< 0.001

Assessing Grid Reliability Limits for Urban Air Mobility Integration

Project Lead: Kai Sun (UTK) **Graduate Students and Research faculty/associates:** Qin Huang (UTK), Peigong Wang (UTK)
Project Duration: 10/2025 – 10/2026
Funding Source: NASA

Summary

Urban Air Mobility (UAM) integration poses an unprecedented stress on distribution grids. High-power charging demands from UAM aircraft can lead to critical voltage drops and thermal overloads. The primary objective of this project is to develop a reliability-driven assessment framework that quantifies both individual bus and system-wide UAM load limits while identifying topology-driven "redlines" that operators must foresee.

The proposed framework, illustrated in Fig. 1, employs a two-stage exhaustive search algorithm and a vulnerability assessment module. In the first stage, the algorithm incrementally increases UAM load (ΔP_i) at candidate buses until safety constraints are breached. In the second stage, by exploring the defined search space, the algorithm identifies the optimal load configuration that maximizes the total UAM integration across the entire distribution system. Then, A voltage sensitivity matrix $S_{V,PL}$ is computed to identify the "weakest" nodes. By deriving a metric γ^k (the sum of absolute sensitivity of Bus *k*), the bus with the highest value is identified as the most vulnerable node in the topology.

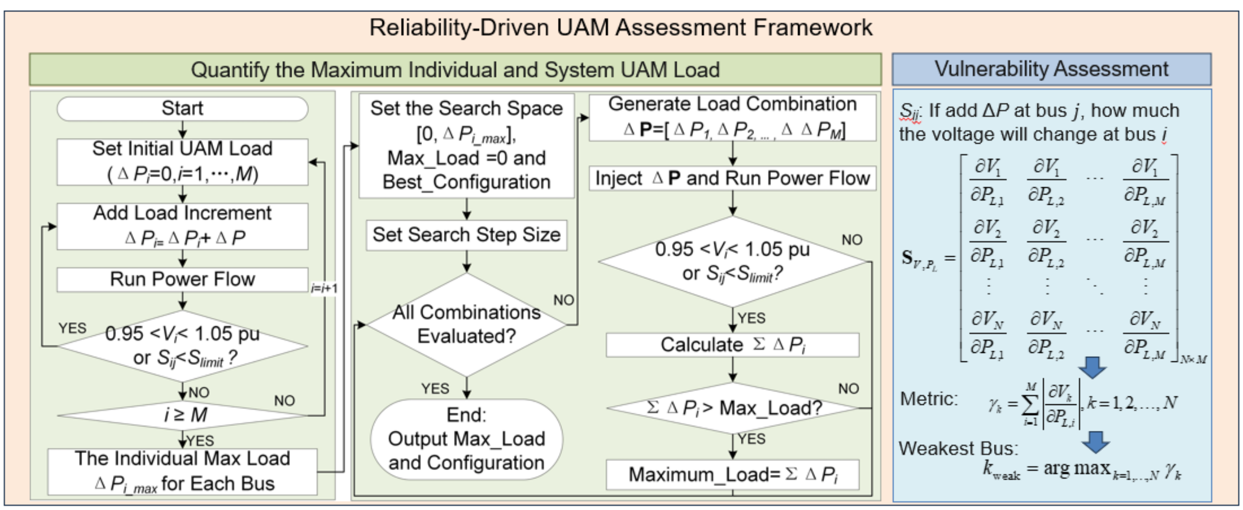

Fig.1. The framework of grid reliability assessment

For the case study, we utilized an upgraded IEEE 34-bus system, as shown in Fig. 2, scaled to a 200 MW urban load center to model dense UAM demand. This distribution testbed is coupled to a regional transmission network, which can capture the cross-layer impacts of scaling UAM loads at the transmission-distribution (T&D) interface.

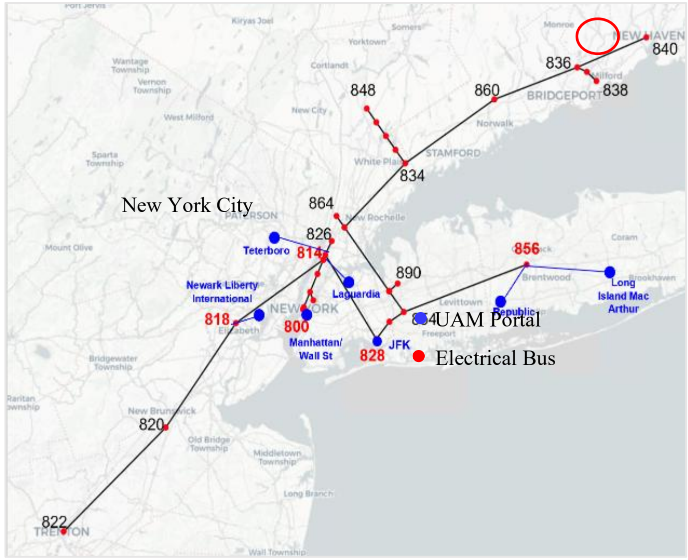

Fig.2. UAM testbed mapped onto the New York City region.

The assessment identified the specific "Individual Max Load" for each candidate bus. Based on these individual limits, the "System-wide Maximum UAM Load" and its corresponding optimal configuration were determined, reaching a total capacity of 84.5 MW (Table 1). Furthermore, the sensitivity analysis identified Bus 840 as the weakest node in the grid, exhibiting the highest sensitivity to load fluctuations ($\gamma^{840} = 1.809\times10^{-3}$).

Table 1. Search Bounds and System-wide Maximum UAM Load

UAM Bus	Search Space	Step Size (MW)	System Optimal Configuration (MW)
814	[0, 11.1375]	0.1	11
828	[0, 6.3]	0.1	6.2
856	[0, 15.4]	0.1	6.0
800	[0, 56.25]	0.5	54.0
818	[0, 5.85]	0.1	5.8
Total Capacity	/	/	**84.5**

The proposed reliability assessment framework quantifies the operational boundaries for large-scale UAM integration and identifies Bus 840 as the most vulnerable node. These findings provide critical decision support for utilities to develop precise grid reinforcement plans and capacity management strategies when addressing future high-penetration transportation loads.